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Cosmological bounds on active-sterile neutrino mixing after Planck data

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Based on PLB 2013, arXiv1303.5368
A. Mirizzi, G. Mangano, N. Saviano, E. Borriello, C. Giunti, G. Miele and O. Pisanti

Experimental anomalies & sterile ν interpretation

Some experimental data in tension with the standard 3ν scenario + oscillations

(...and sometimes in tension among themselves....)

Kopp at al., 2013

1. *$\overline{\nu}_e$ appearance signals*

   - excess of $\overline{\nu}_e$ originated by initial $\overline{\nu}_\mu$: LSND/ MiniBooNE

     A. Aguilar et al., 2001

     A. Aguilar et al., 2010

2. *$\overline{\nu}_e$ and ν_e disappearance signals*

   - deficit in the ν_e fluxes from nuclear reactors (at short distance)

     Mention et al.2011

   - reduced solar $\overline{\nu}_e$ event rate in Gallium experiments

     Acero, Giunti and Lavder, 2008

     Giunti and Lavder, 2011

     Kopp, et al. 2011

All these anomalies, if interpreted as oscillation signals, point towards the possible existence of ***1*** (or more) ***sterile neutrino*** with $\Delta m^2 \sim O\,(\mathrm{eV}^2)$ and $\theta_s \sim O\,(\theta_{13})$

Many analysis have been performed → 3+1, 3+2 schemes

see Kopp's talk

Radiation Content in the Universe

At T $<$ m_e , the radiation content of the Universe is

$$\varepsilon_R = \varepsilon_\gamma + \varepsilon_\nu + \varepsilon_x$$

The non-e.m. energy density is parameterized by the effective numbers of neutrino species N_{eff}

$$\boxed{\varepsilon_\nu + \varepsilon_x = \frac{7}{8}\frac{\pi^2}{15}T_\nu^4 N_{\text{eff}} = \frac{7}{8}\frac{\pi^2}{15}T_\nu^4 (N_{\text{eff}}^{\text{SM}} + \Delta N)}$$

$N_{\text{eff}}^{\text{SM}} = 3.046$ *due to non-instantaneous neutrino decoupling*

(+ oscillations)

Mangano et al. 2005

At T~ m_e, e^+e^- pairs annihilate heating photons. Since $\mathbf{T_{dec}(\nu)}$ is close to $\mathbf{m_e}$, neutrinos share a small part of the entropy release

$\Delta N =$ Extra Radiation: axions and axion-like particles, **sterile neutrinos** (totally or partially thermalized), neutrinos in very low-energy reheating scenarios, relativistic decay products of heavy particles...

Cosmological hints for extra radiation

Extra d.o.f. (i.e. sterile neutrinos) impact the cosmological observables :

✓ **BBN** (through the expansion rate H and the direct effect of ν_e and $\overline{\nu}_e$ on the n-p reactions)

BBN(standard) → $N_{\rm eff} \leq 4$ (at 95% C.L)

Mangano and Serpico, 2011
Hamman et al., 2011
Pettini and Cooke, 2012

with only a small significance preference for $N_{\rm eff}$ > stand.value

✓ **CMB & LSS** (sound horizon, matter-radiation equality, anisotropic stress, damping tail, small scale matter PS)

Slight preference for $N_{\rm eff} > 3.046$

Hints for extra radiation reduce over the years

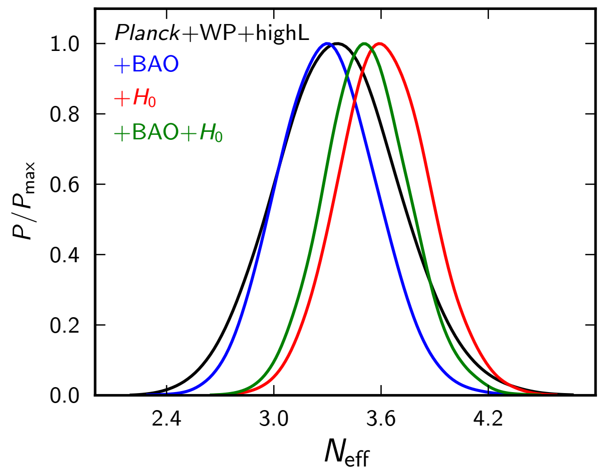
Komatsu et al., 2008,
Komatsu et al., 2010
G. Hinshaw, et al.2013
J.L.Sievers et al. 2013

$N_{\rm eff}$ *and* Σm_ν *constraints* **after Planck**

$N_{\rm eff} = 3.30 \pm 0.54$ (95 % C.L.; Planck+WP+highL+BAO)

compatible with the standard value at 1-σ

Gorski & Lattanzi's talks



Planck XVI, 2013

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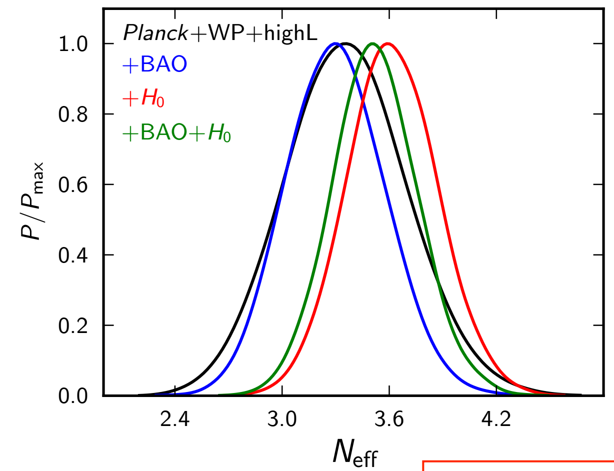

Planck XVI, 2013

Including the H_0 value from HST...

$N_{\mathrm{eff}} = 3.52 \pm 0.48$ (95 % C.L.; Planck+WP+highL+BAO + H0)

Indeed

$H_0^{\mathrm{Planck}} = (63.3 \pm 1.2)$ km s^{-1} Mpc^{-1}

$H_0^{\mathrm{HST}} = (73.3 \pm 2.4)$ km s^{-1} Mpc^{-1}

Not trivial issue:

- unresolved astrophysical systematic effects
- beyond standard ΛCDM model (HOT DM: sterile)

see M. Wyman et al., 2013 and Hamann and Hasenkamp 2013

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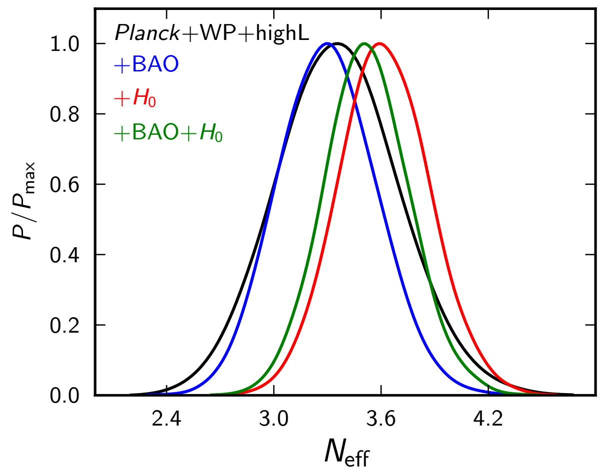

Planck XVI, 2013

bounds on ν mass

model	**Planck +**	**mass bound (eV) (95% C.L.)**
3 degenerate ν_a	WP+HighL+BAO	$\Sigma m_\nu < 0.23$
Joint analysis $N_{\rm eff}$ & 3 degen ν_a	WP+HighL+BAO	$N_{\rm eff} = 3.32 \pm 0.54$ $\Sigma m_\nu < 0.28$
Joint analysis $N_{\rm eff}$ & 1 mass ν_s	WP+HighL+BAO	$N_{\rm eff} < 3.80$ $m^{\rm eff}_{\nu s} < 0.42$

$$m_{\nu s}^{\rm eff} \equiv (94,1\ \Omega_\nu h^2)\mathrm{eV}$$

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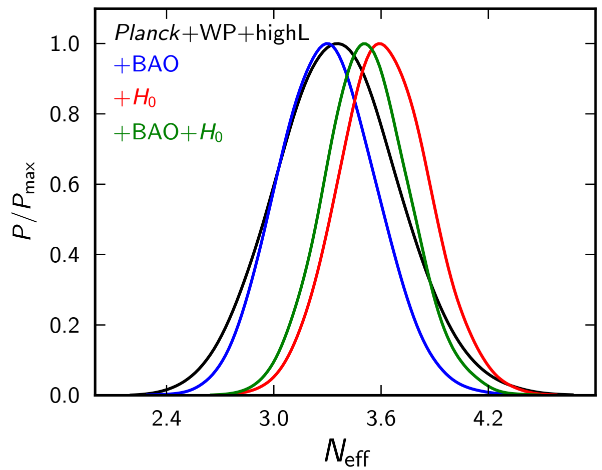

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Active-sterile flavor evolution

Sterile ν are produced in the Early Universe by the mixing with the active species

✳ No primordial sterile neutrino is present

- Describe the ν ensemble in terms of 4x4 density matrix $\varrho(x,y) = \begin{pmatrix} \varrho_{ee} & \varrho_{e\mu} & \varrho_{e\tau} & \varrho_{es} \\ \varrho_{\mu e} & \varrho_{\mu\mu} & \varrho_{\mu\tau} & \varrho_{\mu s} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} & \varrho_{\tau s} \\ \varrho_{se} & \varrho_{s\mu} & \varrho_{s\tau} & \varrho_{ss} \end{pmatrix}$

- introduce the dimensionless variables $x \equiv m\ a;\ y \equiv p\ a;\ z \equiv T_\gamma\ a;$

  with m = arbitrary mass scale; a= scale factor, a(t) → 1/T

- denote the time derivative $\partial_t \to \partial_t - Hp\,\partial_{\mathbf{p}} = Hx\,\partial_x$, H the Hubble parameter $\boxed{\overline{H} \equiv \frac{x^2}{m} H}$

➢ the EoM become:

$$i\frac{d\varrho}{dx} = +\frac{x^2}{2m^2\,y\,\overline{H}}\left[\mathrm{M}^2, \varrho\right] + \frac{\sqrt{2}G_F\,m^2}{x^2\,\overline{H}} \times \left[-\frac{8\,y\,m^2}{3\,x^2}\left(\frac{\mathsf{E}_\ell}{m_W^2} - \frac{\mathsf{E}_\nu}{m_Z^2}\right) + \mathsf{N}_\nu, \varrho\right] + \frac{x\,\hat{C}[\varrho(y)]}{m\,\overline{H}}$$

Sigl and Raffelt 1993;
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MSW effect with background medium

(refractive effect)

charged lepton asymmetry subleading ($O(10^{-9})$) ➜

➜ 2^{th} order term: "symmetric" matter effect

sum of e^- - e^+ energy densities ε

$\mathsf{E}_\ell \equiv \mathrm{diag}(\varepsilon_e, 0, 0, 0)$

Sigl and Raffelt 1993;
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self-interactions of ν with the ν background:

off-diagonal potentials ➠ non-linear EoM

Sigl and Raffelt 1993;
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symmetric term

$\propto (\varrho + \overline{\varrho})$

Sigl and Raffelt 1993;
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asymmetric term

$\propto (\varrho - \overline{\varrho}) \leftrightarrow L$

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Collisional term $\propto G_F^2$

creation, annihilation and all the momentum exchanging processes

Sigl and Raffelt 1993;
McKellar & Thomson, 1994
Dolgov et al., 2002.

Bounds on active-sterile mixing parameters after Planck

✔ sterile abundance by flavor evolution of the active-sterile system for 3+1 scenario (to be compared with the Planck constraints)

✔ 2 sterile mixing angles (+ 3 active) $10^{-5} \leq \sin^2\theta_{i4} \leq 10^{-1}$ (i= 1,2)

✔ sterile mass-square difference $\Delta m^2_{st} = \Delta m^2_{41}$ (+ 2 active) $10^{-5} \leq \Delta m^2_{41}/\mathrm{eV}^2 \leq 10^2$

✔ *average-momentum* approximation (single momentum): $\varrho_{\mathbf{p}}(T) = f_{FD}(p)\rho(T)$ $(\langle p \rangle = 3.15\ T)$

✔ conservative scenario: vanishing primordial neutrino asymmetry

*Mirizzi, Mangano, **N.S**. et al 2013,* arXiv:1303.5368

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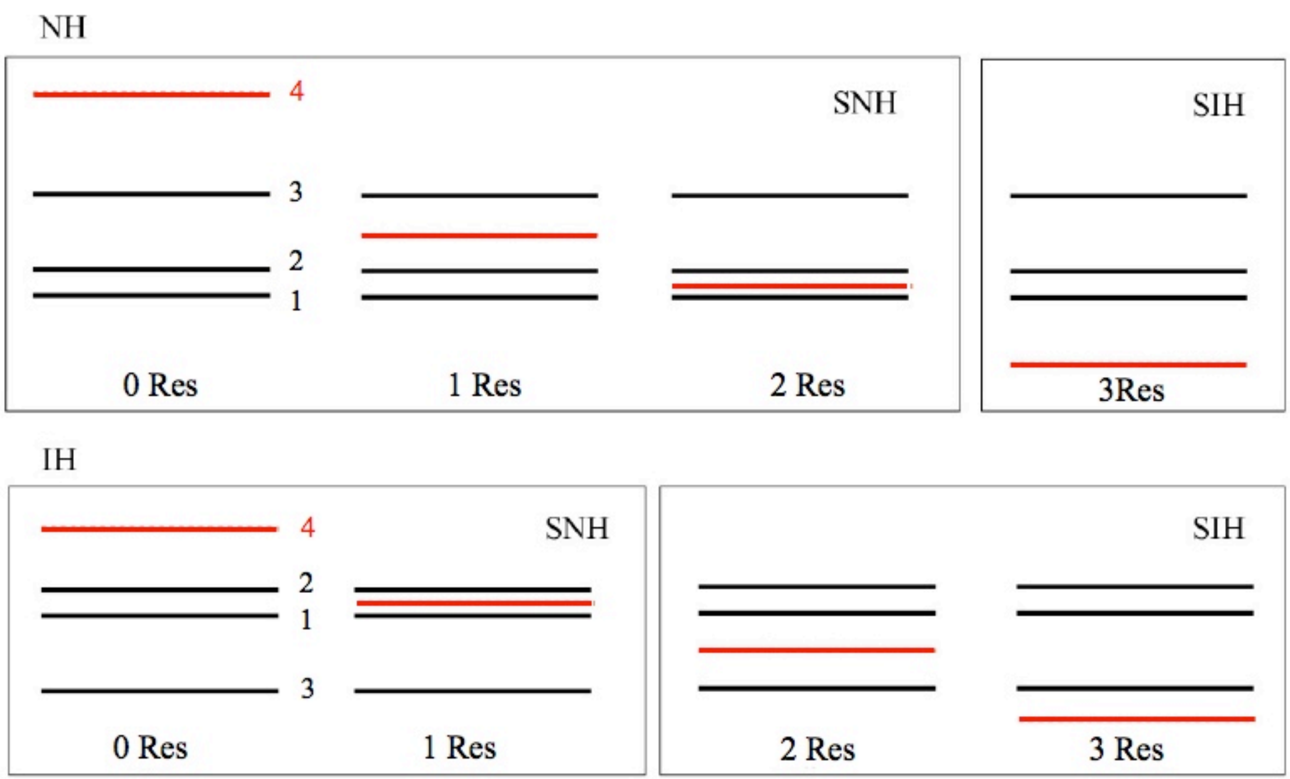

In the sterile sector:

resonances associated with

Δm^2_{4i} θ_{i4}

$i=1,2,3$

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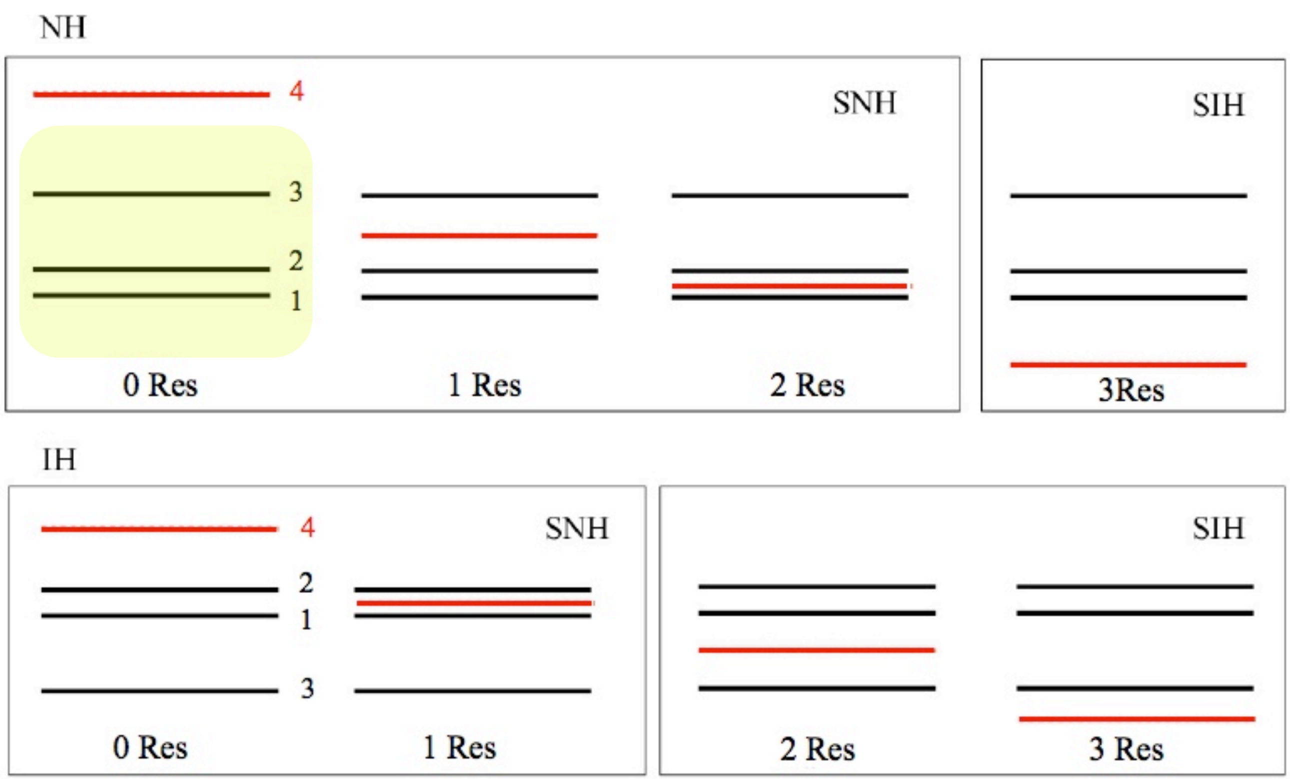

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i=1,2,3

Active: NH, $\Delta m^2_{31} > 0$; IH, $\Delta m^2_{31} < 0$

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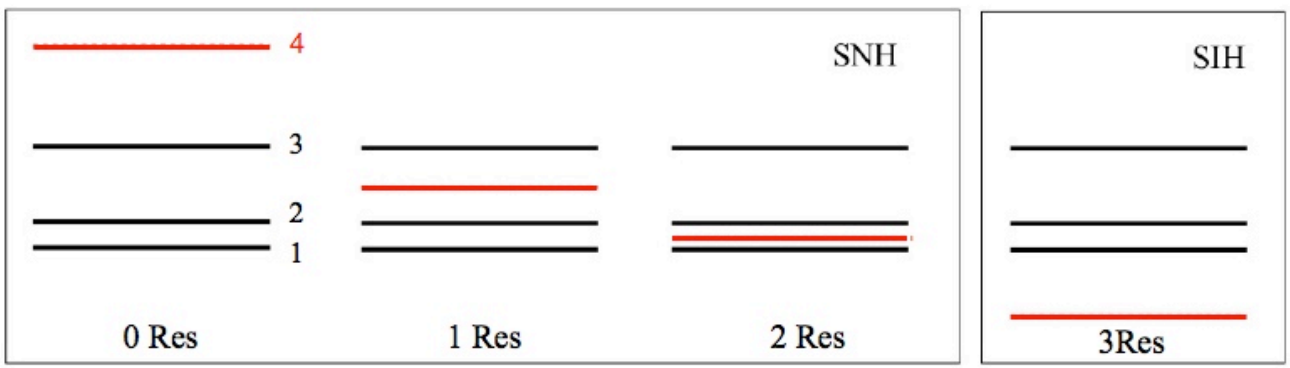
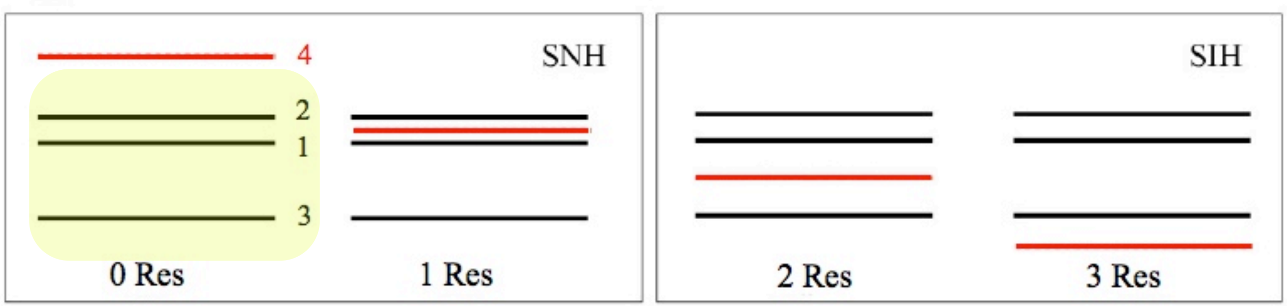
NH



IH



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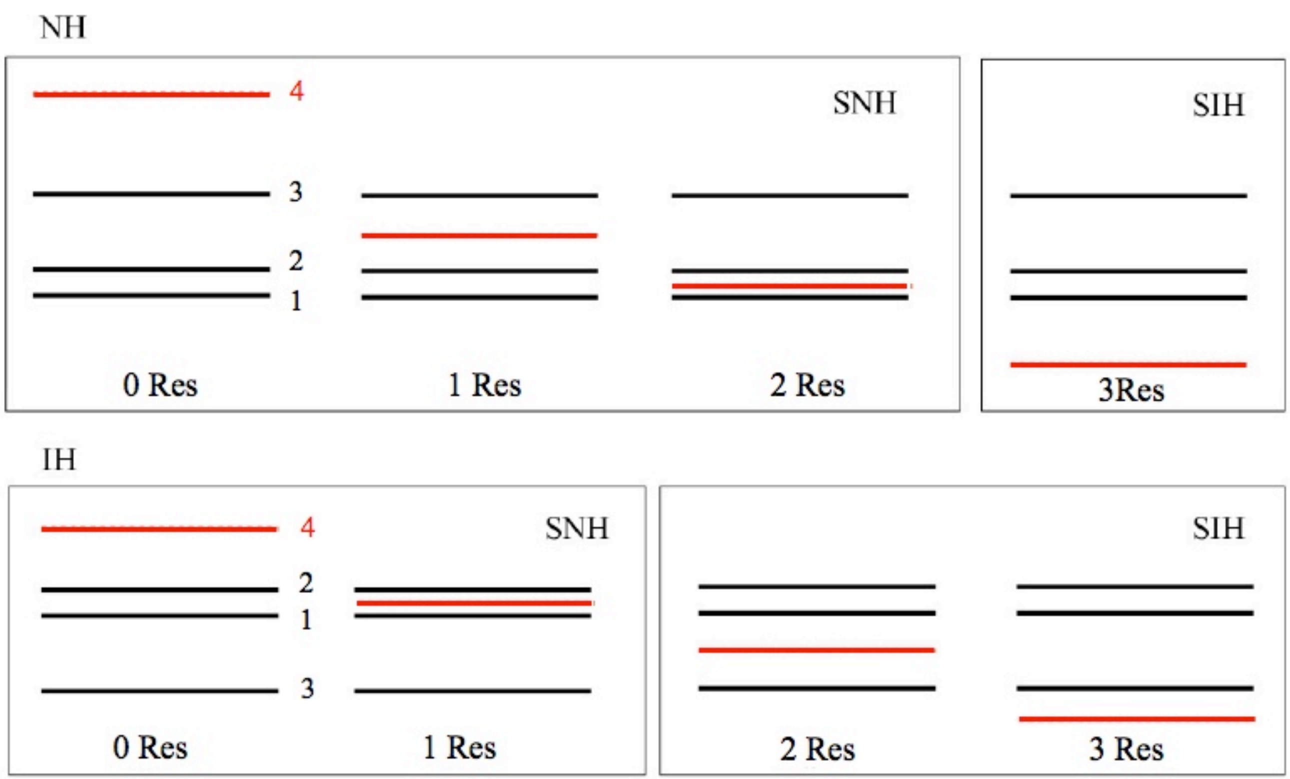

In the sterile sector:

resonances associated with

Δm^2_{4i} θ_{i4}

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Active	NH, $\Delta m^2_{31} > 0$ IH, $\Delta m^2_{31} < 0$
Sterile	SNH, $\Delta m^2_{41} > 0$ SIH, $\Delta m^2_{41} < 0$

Sterile production: dependence on the active-sterile neutrino mass ordering

- The resonance condition can be satisfied only for $\Delta m^2_{4i} < 0$

- When more than one Δm^2_{4i} is negative, multiple resonances can occur

Evolution of sterile density component ρ_{ss} for 3 sterile mass splittings

$\Delta m^2_{41} = 5 \times 10^{-2}$ eV^2 (NO reson., NH + SNH)

$\Delta m^2_{41} = 10^{-5}$ eV^2 (2 reson., NH + SNH)

$\Delta m^2_{41} = - 10^{-5}$ eV^2 (3 reson., NH + SIH)

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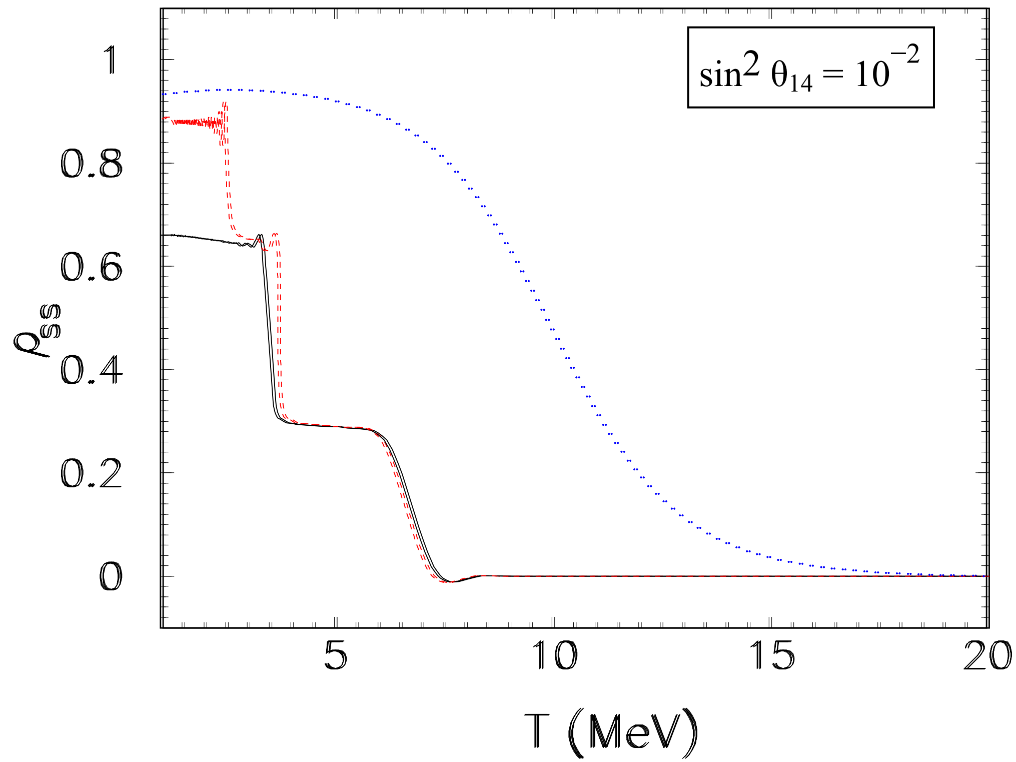
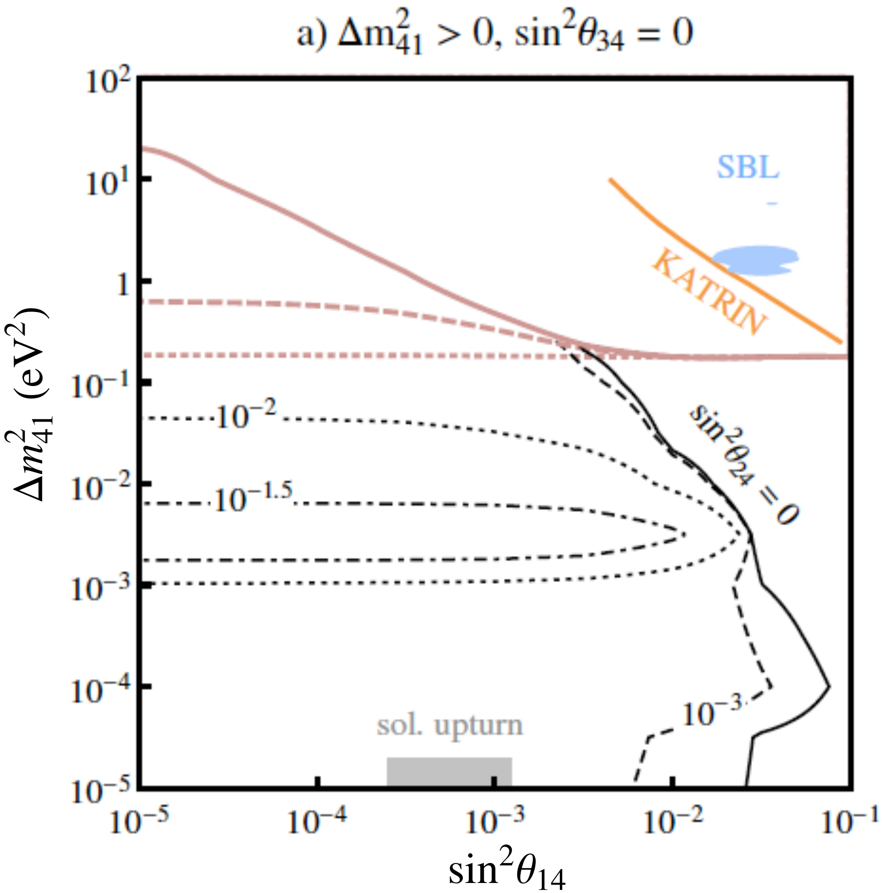


Bounds on active-sterile mixing parameters after Planck
... our results



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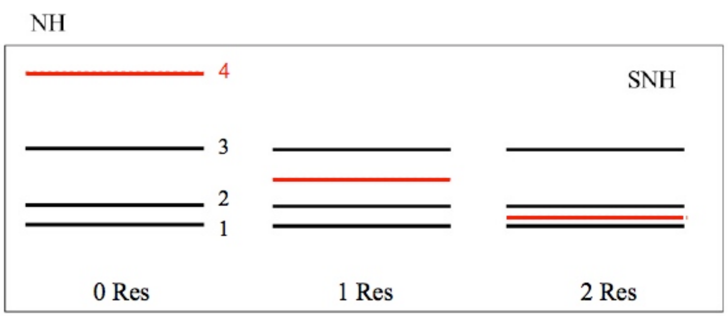
- ✓ Normal active hierarchy
- ✓ Normal sterile hierarchy

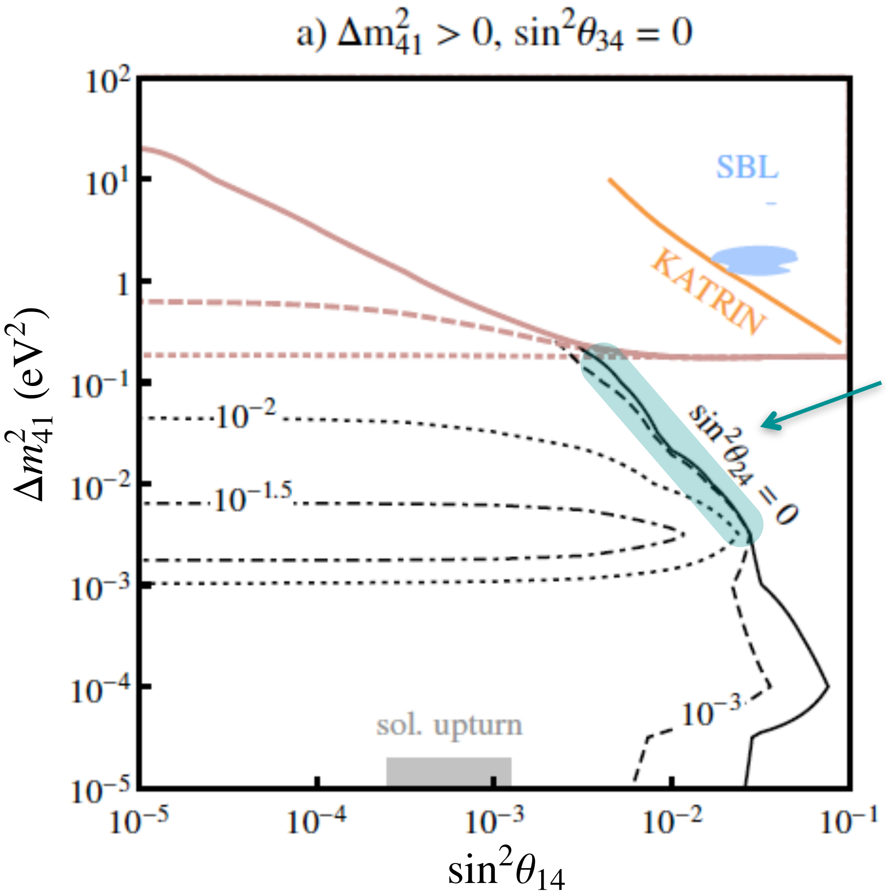


Radiation bounds

- Black curves imposing the 95% C.L. Planck constraint $N_{\rm eff} < 3.8$ on ours $N_{\rm eff} = \frac{1}{2} Tr[\rho + \bar{\rho}]$

The excluded regions are those on the right or at the exterior of the black contours.

Bounds on active-sterile mixing parameters after Planck ... our results



Mirizzi et al 2013, arXiv1303.5368

- ✓ Normal active hierarchy
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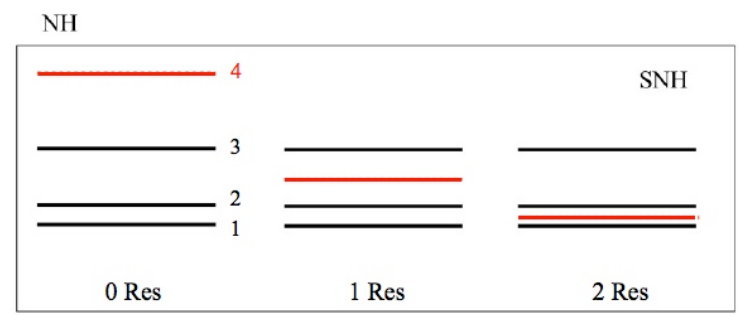
simple behavior for $\theta_{24} \simeq 0$ and for large sterile mass

see also Hannestad, Tamborra and Tram 2012



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Bounds on active-sterile mixing parameters after Planck

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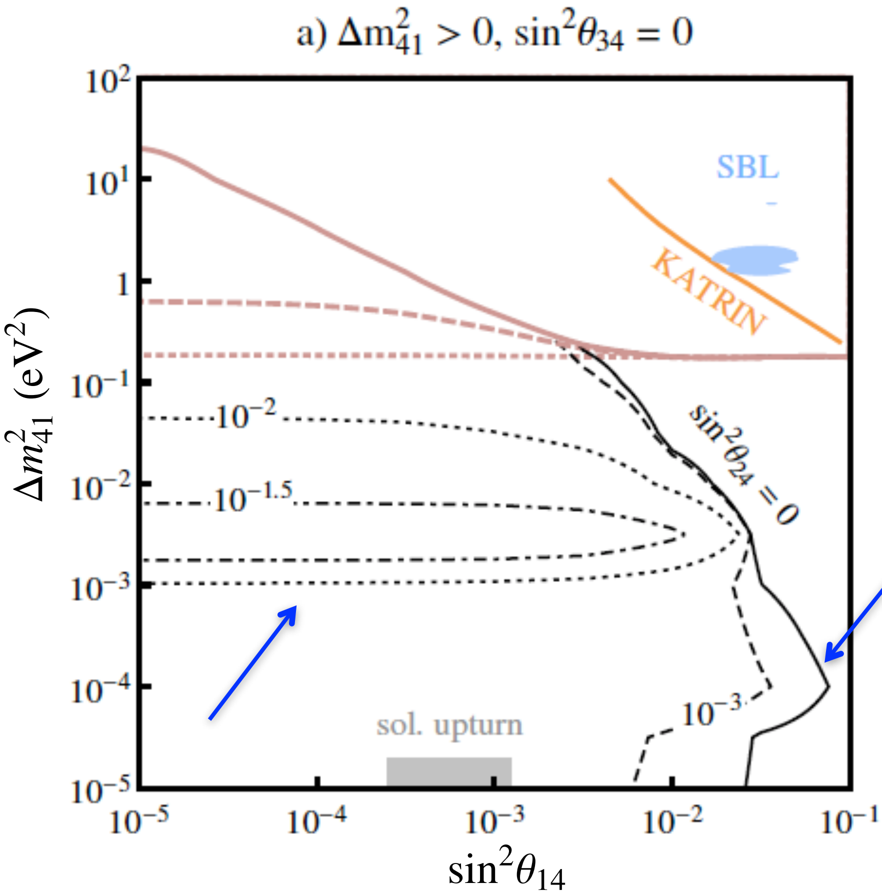
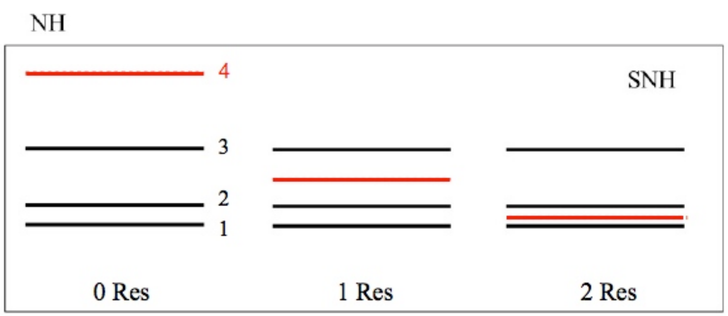


Mirizzi et al 2013, arXiv1303.5368

- ✓ Normal active hierarchy
- ✓ Normal sterile hierarchy

complex behavior for small sterile mass due to resonances and for $\theta_{24} > 0$



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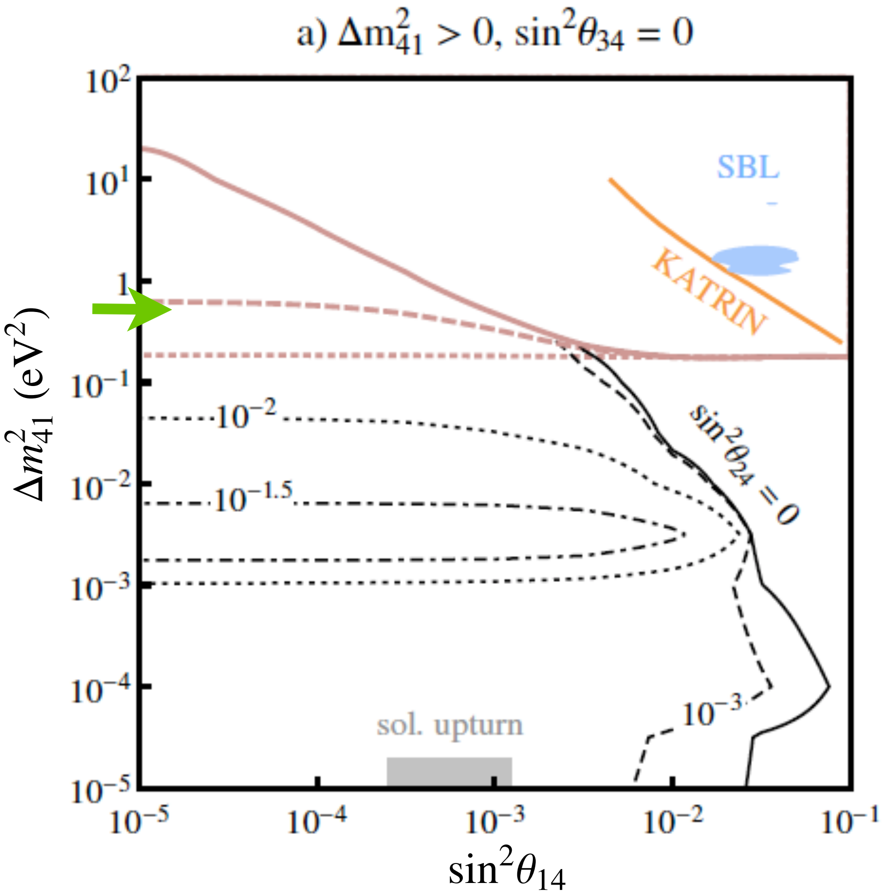

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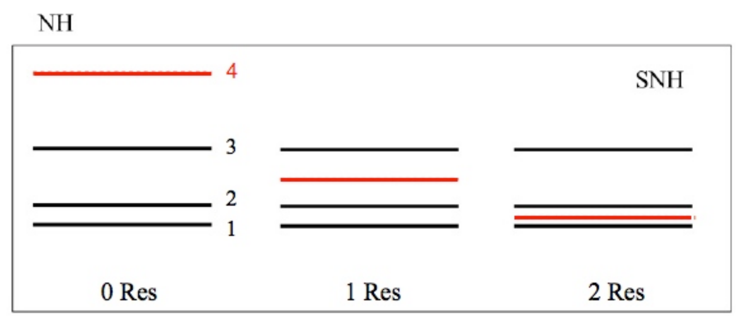

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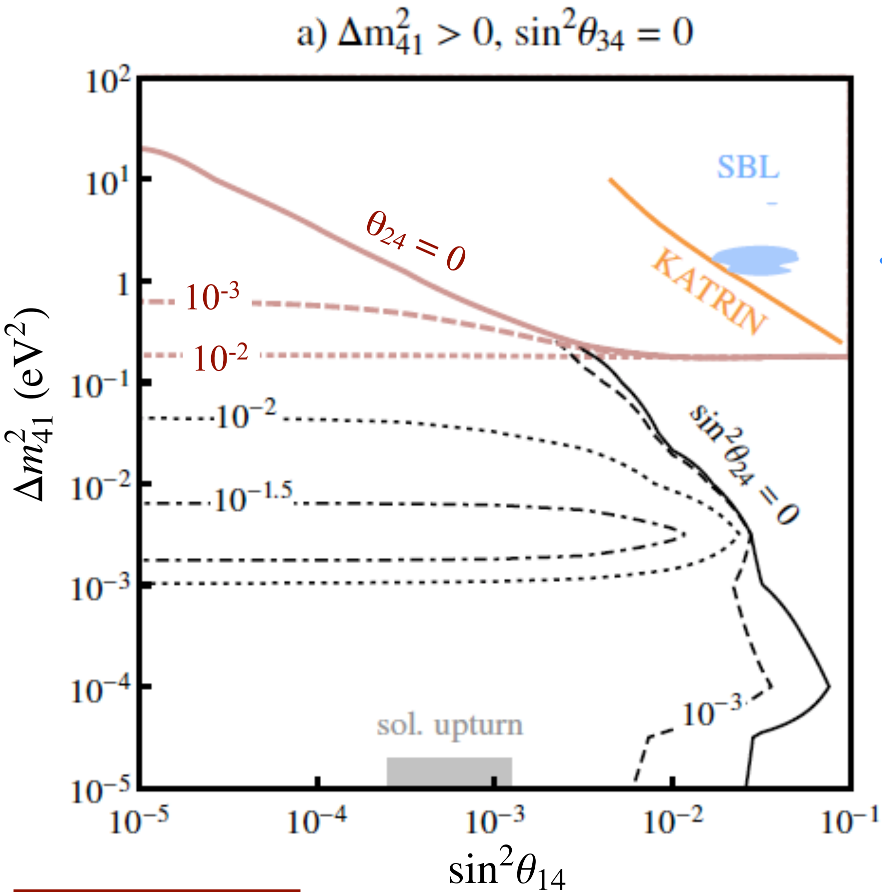
The excluded regions are those on the right or at the exterior of the black contours.

Note: above m ~ $\mathcal{O}$(1 eV), sterile ν are not relativistic anymore at CMB → **NO radiation constraint**

BUT mass constraints become important

Bounds on active-sterile mixing parameters after Planck
... our results



$\sin^2\theta_{24}$= 10^{-2}, 95%C.L. allowed region from global analysis of SBL (Giunti et al.)

Mirizzi et al 2013, arXiv1303.5368

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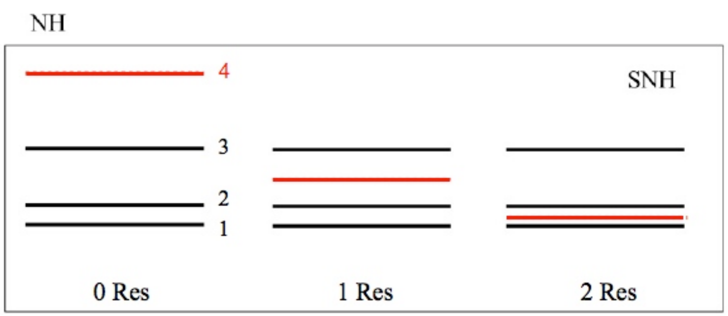


Mass bounds

- Red curves imposing the 95% C.L. Planck constraint $m^{eff}_{\nu s} < 0.42 \Leftrightarrow \Omega_\nu h^2 < 4.5\ 10^{-3}$ on ours

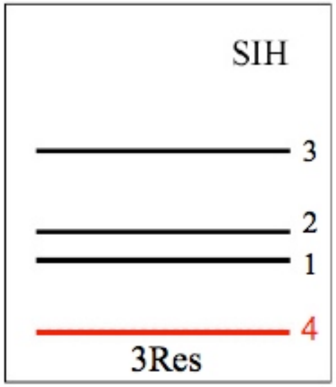
$$\Omega_\nu h^2 = \frac{1}{2}\frac{[\sqrt{\Delta m^2_{41}}(\rho_{ss}+\bar{\rho}_{ss})]}{94.1\ \ \mathrm{eV}}$$

The excluded regions are those above the red contours.

Bounds on active-sterile mixing parameters after Planck ... our results

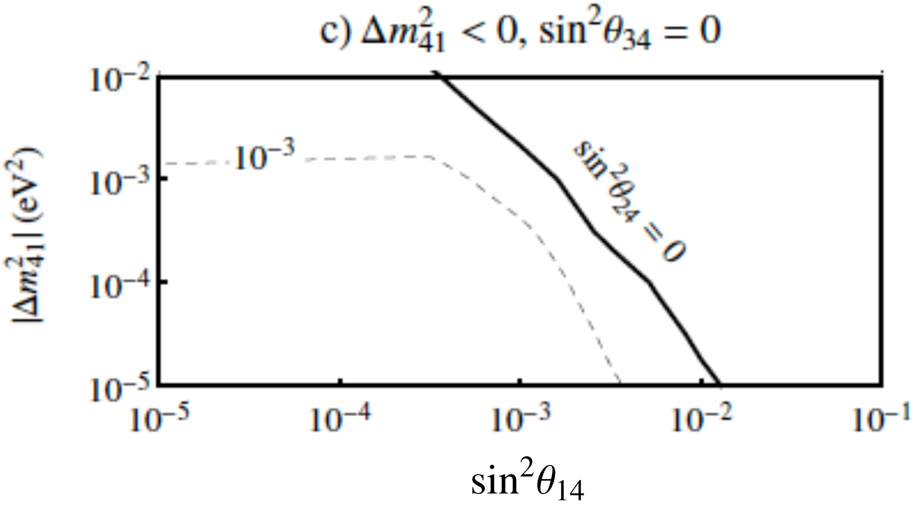
Mirizzi et al 2013, arXiv1303.5368

- ✓ Normal active hierarchy
- ✓ **Inverted** sterile hierarchy



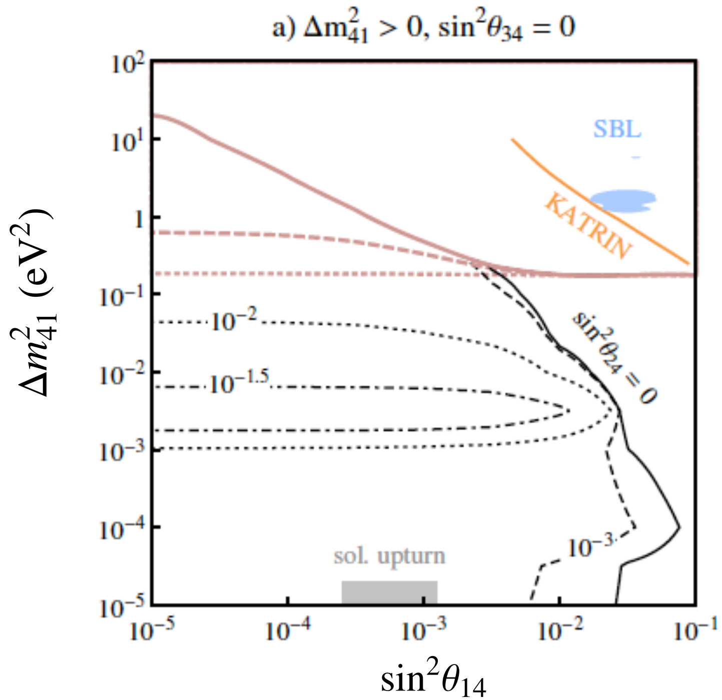
additional 4-1 resonance: increase of the sterile production

Radiation bounds



The excluded regions for the same values of the mixing angles are larger than the corresponding ones in the normal sterile hierarchy.

Bounds on active-sterile mixing: CONCLUSIONS



Mirizzi et al 2013, arXiv:1303.5368

- *The sterile neutrino parameter space is severely constrained.*
- *Excluded area from the* ***mass bound*** *covers the region accessible by current and future laboratory experiments.*
- ***Sterile ν with m ~ $\mathcal{O}$(1 eV) strongly disfavored***

Bounds on active-sterile mixing: the end of the story?

1. Suppression of the sterile production

✓ In the presence of large $\nu-\bar{\nu}$ asymmetries ($\sim 10^{-2}$) sterile production strongly suppressed. Planck mass bound can be evaded

*Mirizzi, **N.S.**, Miele, Serpico 2012*

✘ Not trivial implication for BNN

Saviano et al., 2013

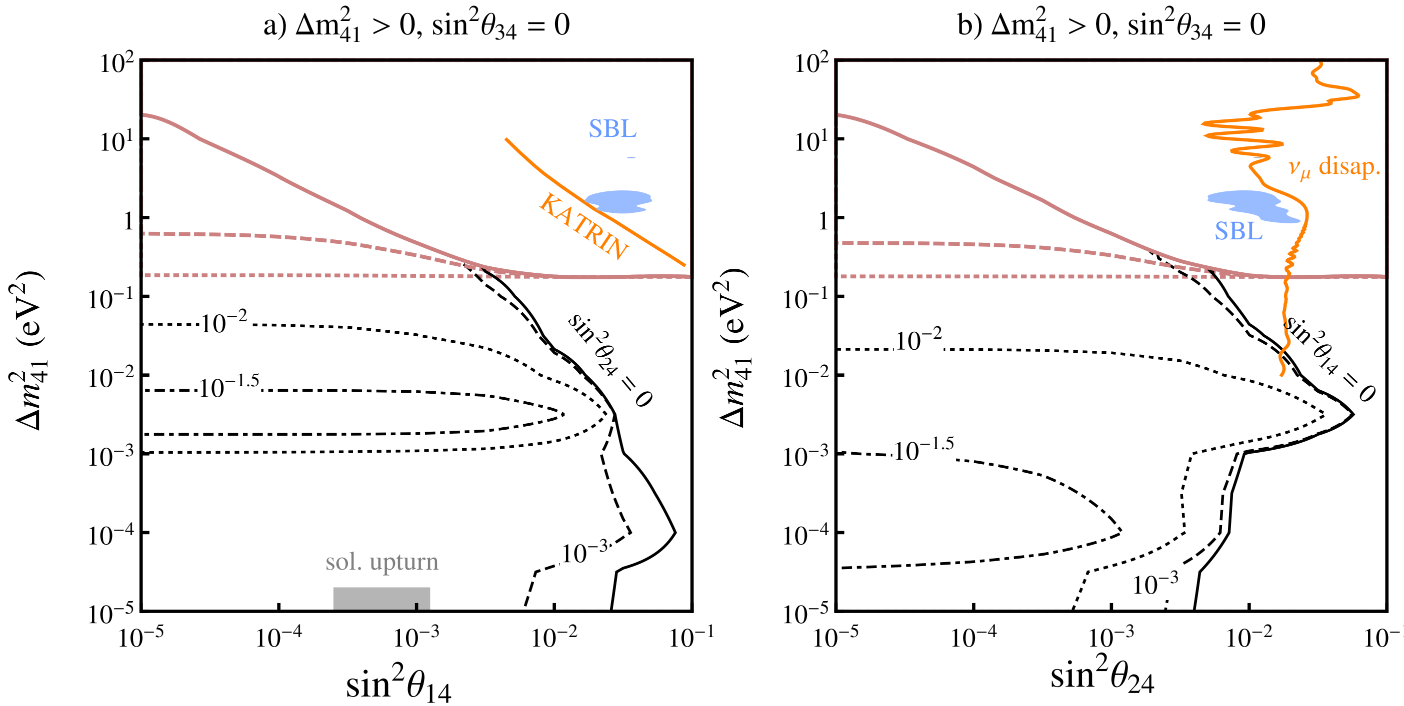
2. If lab ν_s would be confirmed …

New physics in the particle sector and also modification of the standard cosmological model

Thank you

Bounds on active-sterile mixing parameters after Planck

... our results



Mirizzi et al 2013, arXiv:1303.5368

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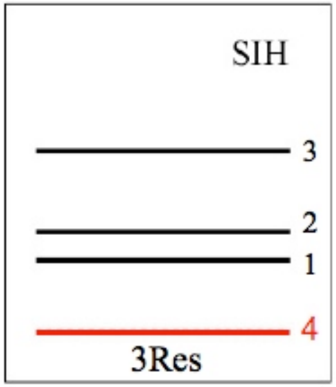
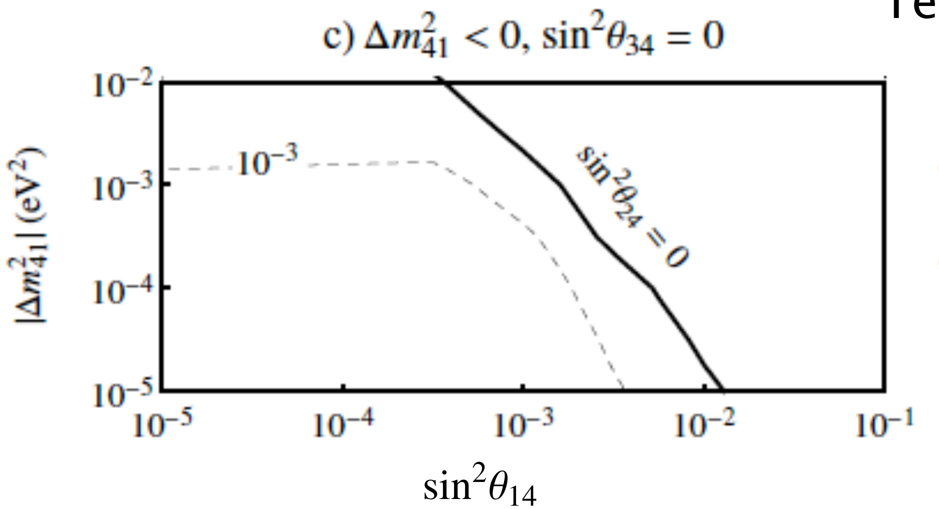
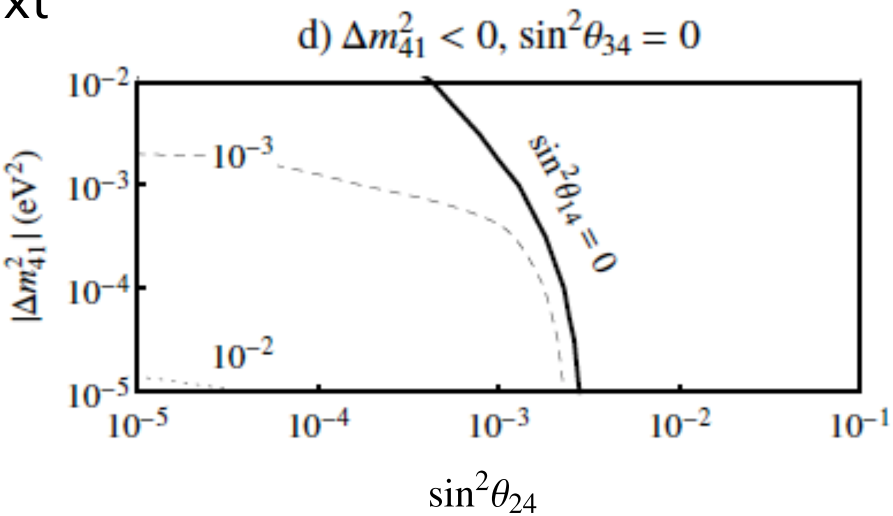


additional 4-1 resonance: increase of the sterile production

Radiation bounds

Text





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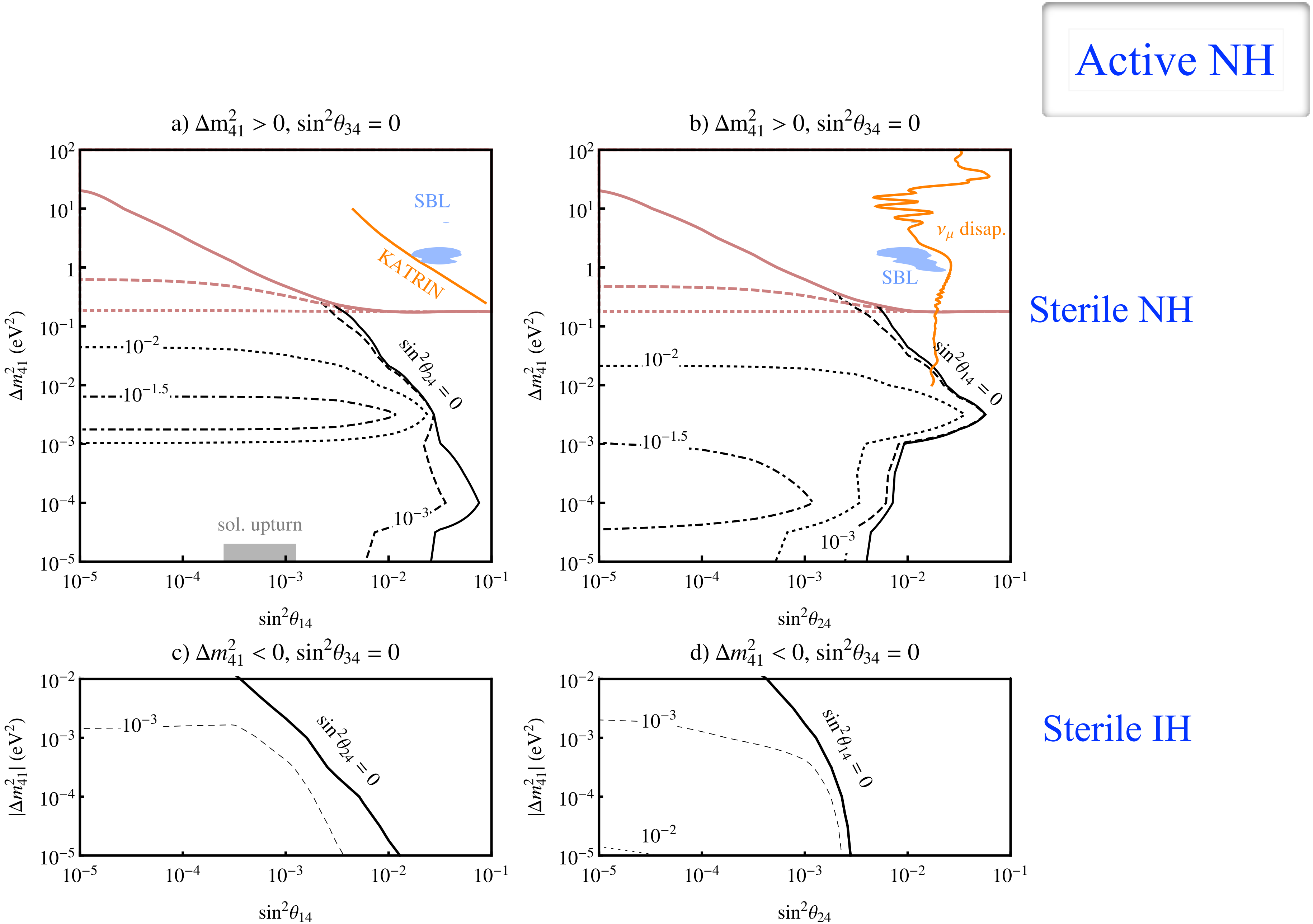
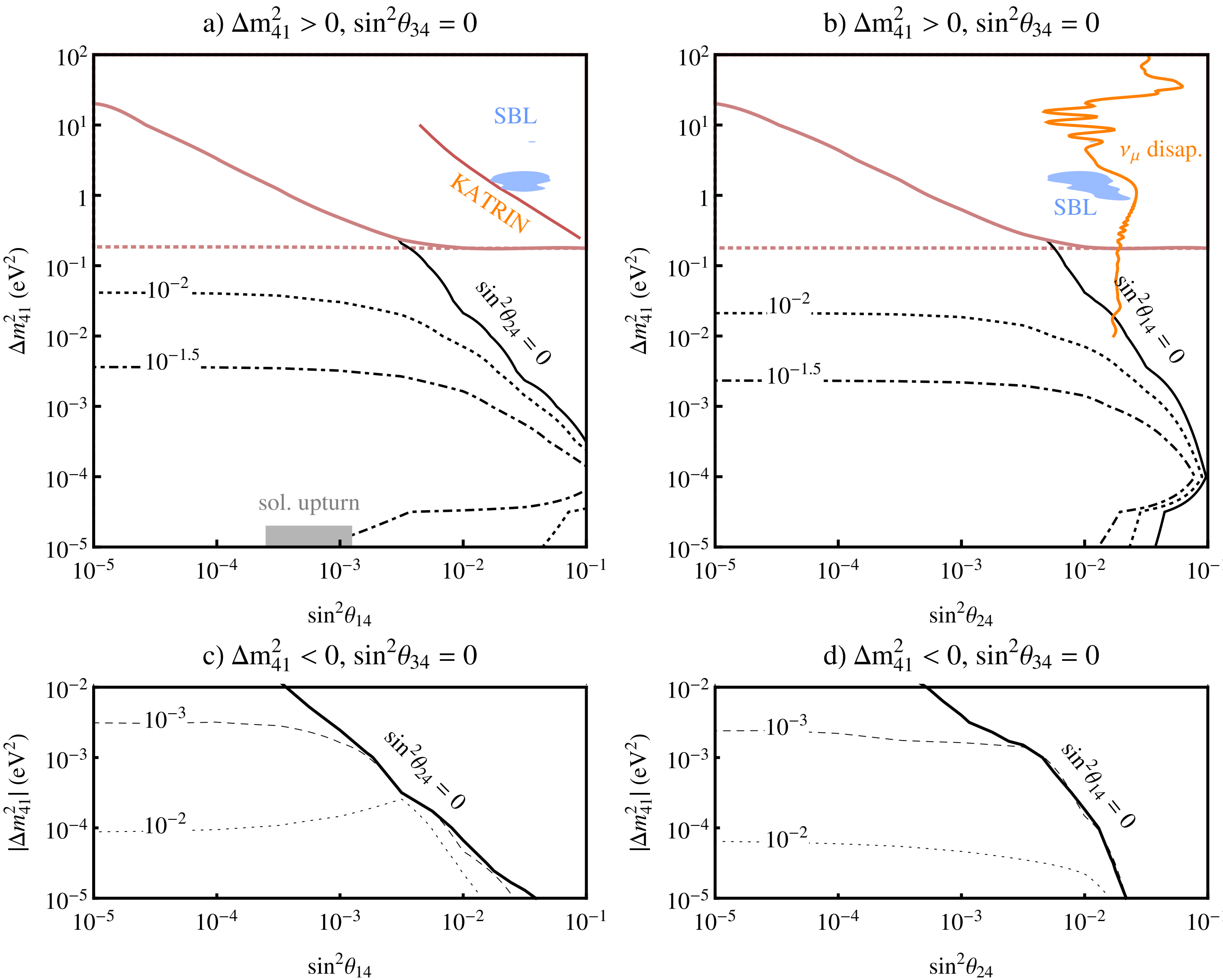


Active NH
a) $\Delta m^2_{41} > 0$, $\sin^2\theta_{34} = 0$
b) $\Delta m^2_{41} > 0$, $\sin^2\theta_{34} = 0$
SBL
KATRIN
ν_μ disap.
$\sin^2\theta_{24} = 0$
$\sin^2\theta_{14} = 0$
10^{-2}
$10^{-1.5}$
10^{-3}
sol. upturn
Δm^2_{41} (eV^2)
$\sin^2\theta_{14}$
$\sin^2\theta_{24}$
Sterile NH
c) $\Delta m^2_{41} < 0$, $\sin^2\theta_{34} = 0$
d) $\Delta m^2_{41} < 0$, $\sin^2\theta_{34} = 0$
$|\Delta m^2_{41}|$ (eV^2)
Sterile IH

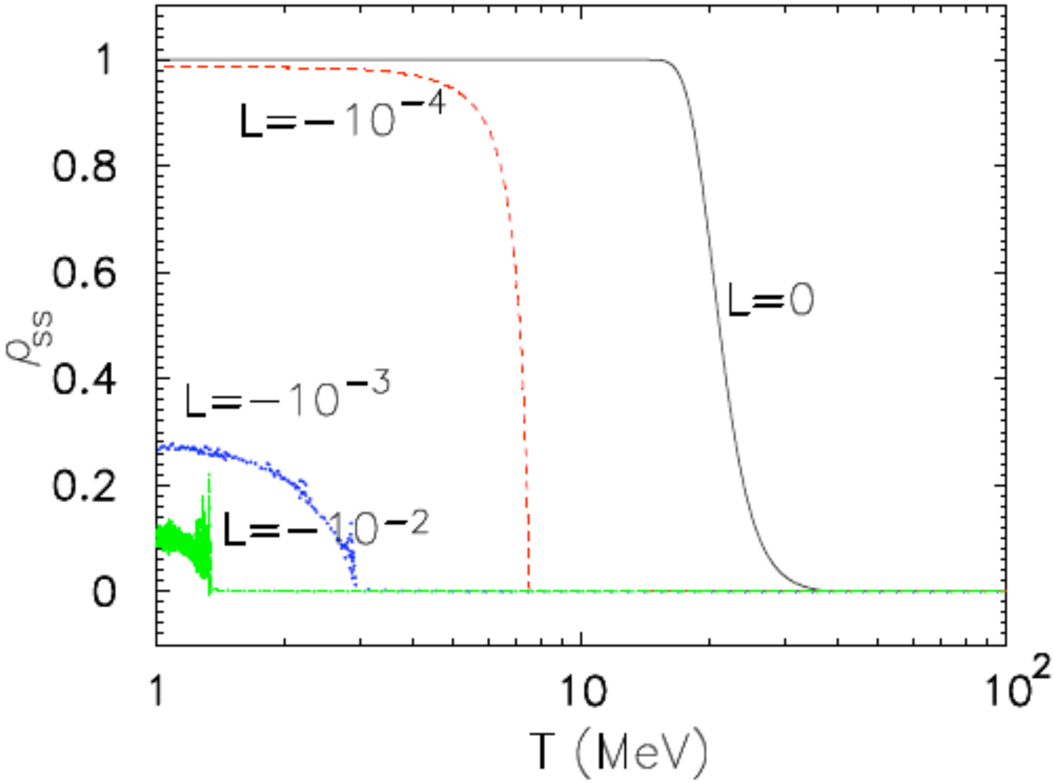
Active IH



Sterile NH

Sterile IH

3 + 1 Scenario



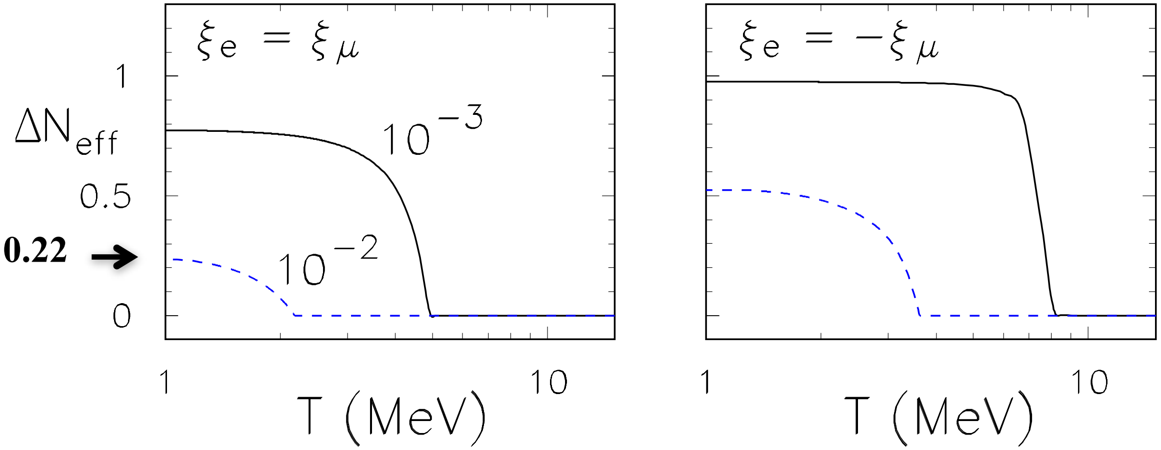
EXPLORATORY STUDY:
AVERAGE (or single)
MOMENTUM APPROX

Mirizzi, N.S., Miele, Serpico 2012
Phys. Rev. D 86, 053009

N_{eff} *from multi-momentum treatment*

✓ Compute N_{eff} as function of the ν ***asymmetry parameter***

looking at the extra contribution $\Delta N_{\text{eff}} = \frac{60}{7\pi^4}\int dy\ y^3 \text{Tr}[\varrho(x,y)+\bar{\varrho}(x,y)] - 2$



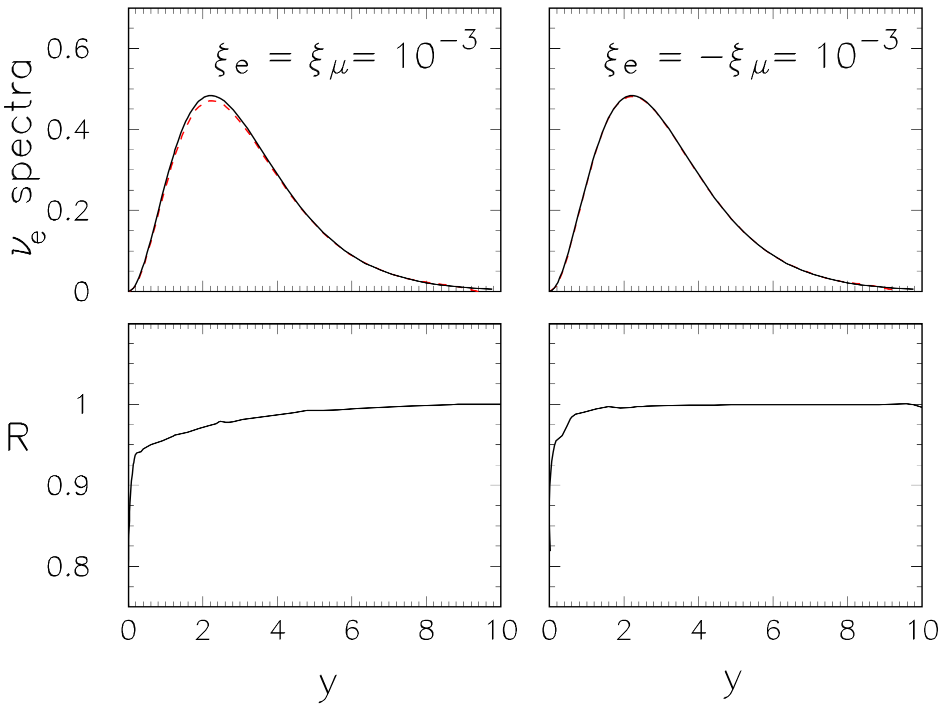
Case	ΔN_{eff}	$\Delta N_{\text{eff}}^{\langle y \rangle}$
$\lvert\xi\rvert \ll 10^{-3}$	1.0	1.0
$\xi_e = -\xi_\mu = 10^{-3}$	0.98	0.89
$\xi_e = \xi_\mu = 10^{-3}$	0.77	0.51
$\xi_e = -\xi_\mu = 10^{-2}$	0.52	0.44
$\xi_e = \xi_\mu = 10^{-2}$	0.22	0.04

Enhancement at most of 0.2 of unity for ΔN with respect to the single-momentum approx.

One needs to consider very large asymmetries in order to significantly suppress the production of sterile neutrinos.

see also *Hannestad, Tamborra and Tram, 2012*

Spectral distortions

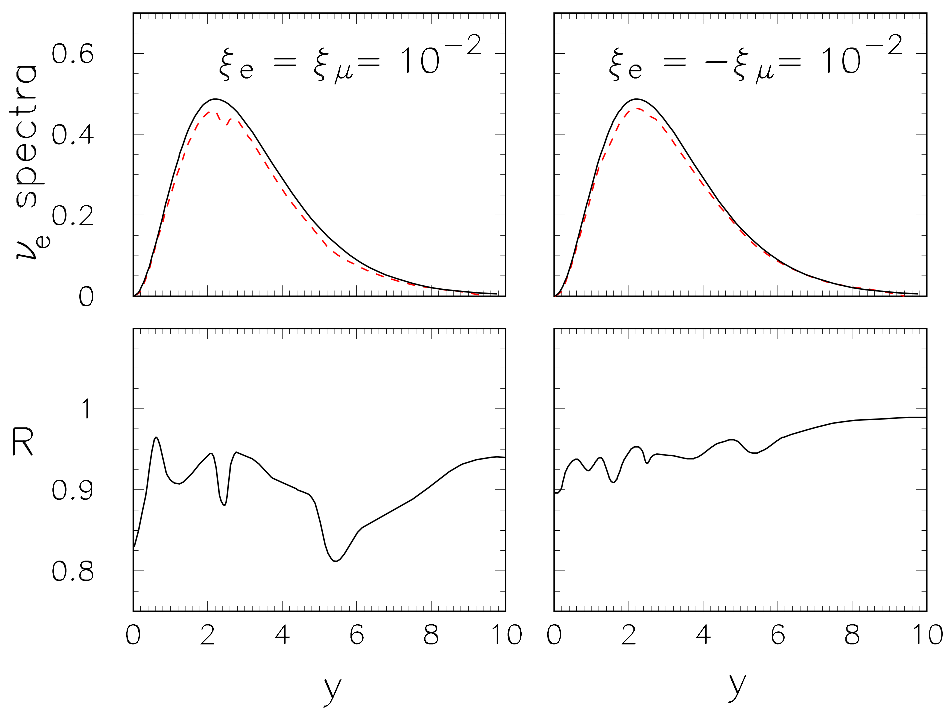


— $y^2\,\rho_{ee}\,(y)$

— $y^2 f_{eq}\,(y, \xi_e)$

$\xi_\nu = \mu_\nu / T$

$$R = \frac{\varrho_{ee}(y)}{f_{eq}(y, \xi_e)}$$



Sizable distortions (especially for $\xi = 10^{-2}$)

→ consequences on primordial yields

Saviano et al, 2013; Phys. Rev. D 87, 073006

Non-trivial implications on BBN

Saviano et al, 2013;
Phys. Rev. D 87, 073006

Case	$\Delta N_{\rm eff}$	$\Delta N_{\rm eff}^{\langle y \rangle}$	Y_p	^{2}H/H $(\times 10^5)$
$\|\xi\| \ll 10^{-3}$	1.0	1.0	0.259	2.90
$\xi_e = -\xi_\mu = 10^{-3}$	0.98	0.89	0.257	2.87
$\xi_e = \xi_\mu = 10^{-3}$	0.77	0.51	0.256	2.81
$\xi_e = -\xi_\mu = 10^{-2}$	0.52	0.44	0.255	2.74
$\xi_e = \xi_\mu = 10^{-2}$	0.22	0.04	0.251	2.64
$\xi_e = \|\xi_\mu\| = 10^{-3}$, no ν_s	~ 0	–	0.246	2.56
$\xi_e = \|\xi_\mu\| = 10^{-2}$, no ν_s	~ 0	–	0.244	2.55
standard BBN	0	0	0.247	2.56

PArthENoPE code *Pisanti et al, 2012*

$$Y_p = \frac{2(n/p)}{1+n/p}$$

Helium mass fraction

Deuterium mainly sensitive to the increase of $N_{\rm eff}$

Helium 4 sensitive both to
- increase of $N_{\rm eff}$
- changes in the weak rates due to the spectral distortions